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Electroreflectance Study of Interband Magneto-Optical Transitions in InAs and InSb at 1.5°K

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MASSACHUSETTS INSTITUTE OF TECHNOLOGY

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ABSTRACT

The transparent electrode electroreflectance technique has been used for interband magneto-optical studies of InAs and InSb at 1.5°K. We report here the first direct experimental observation of the spin-orbit splitting ($\Delta = 0.38 \pm 0.01$ eV), the effective mass ($m_{so} = 0.14 \pm 0.01\ m_o$) and the effective g-factor ($g_{so} = 13.0 \pm 1.0$) for the split-off band at $\vec{k} = 0$ in InAs.

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ELECTROREFLECTANCE STUDY OF INTERBAND MAGNETO-OPTICAL TRANSITIONS IN InAs AND InSb AT 1.5°K

Previous studies of magnetoelectroreflectance at room temperature,[1] using the electrolyte method of Cardona and co-workers,[2] have demonstrated the enhancement in sensitivity obtainable with electric field modulation of magneto-optical phenomena in semiconductors. The electrolyte method is suitable for work at temperatures above that of dry ice, and at wavelengths shorter than 2.5 μ in the infrared. In the work discussed here a modification of the transparent electrode method of Seraphin and co-workers[3] has been used to extend the measurements to liquid helium temperature and to wavelengths further into the infrared.[4] We report here the first direct experimental observation of the spin-orbit splitting Δ, the effective mass m_{so}, and g-factor g_{so} of the split-off valence band at $\vec{k} = 0$ in InAs. Further experimental results are given for the direct valence and split-off valence to conduction band transitions in InSb. The latter results are similar to those reported by Aggarwal[5] using the piezo-reflectance technique.

The transparent electrode technique as described in Ref. 3 uses a thin insulating spacer between the etched sample surface and a SnO_2-glass electrode. The DC and AC electric fields are applied between the transparent electrode and sample, and the reflected light synchronously detected at the frequency of the AC electric field. Unless an optical matching material is used between the electrode and the insulator, there is a large unwanted wavelength dependent signal caused by interference of light reflected from the insulator/sample and electrode/insulator interfaces. This is modulated at the AC frequency by the mechanical vibration due to the electrical forces. Most optical matching fillers craze and become opaque when taken below 77°K. For this reason we have used a mechanically integrated thin film package, shown schematically in the lower insert of Fig. 1. The spacer layer, photo-resist material[6] of thickness about 1 μ, was spin coated onto the etched sample surface. A 65% transmitting Ni film (of surface resistance 1000 ohms per square) was deposited on this as

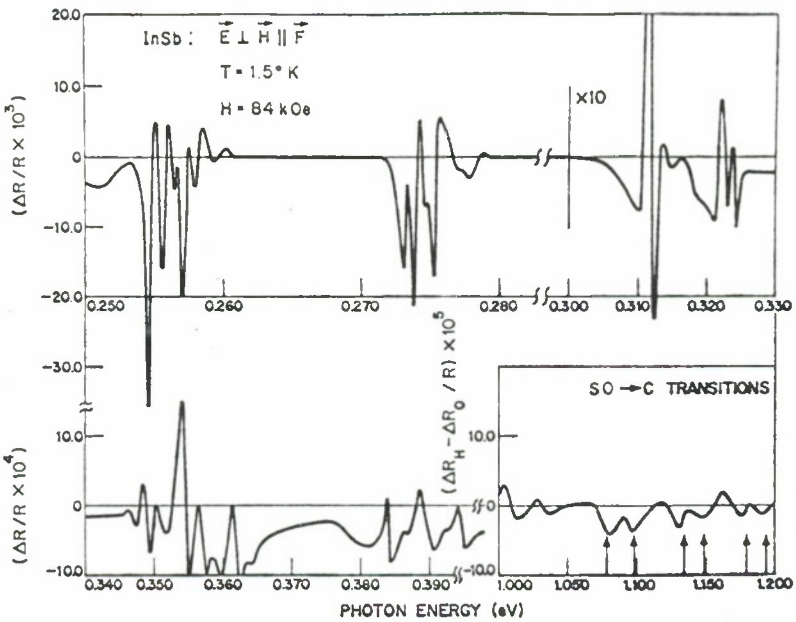

Fig. 1. Interband magnetoelectroreflectance in InAs for H = 84 kOe at T = 1.5°K. Inset shows the spectrum of the split-off valence to conduction band transitions for left and right circularly polarized light (σ_L and σ_R). The experimental arrangement of the electroreflectance package is also shown in the inset.

the transparent electrode. A thick gold tab was deposited at one end of the Ni, and a connecting foil or wire fastened to this with a conductive epoxy cement.[7] With this arrangement it was possible to establish an electric field at the surface of the sample of $\sim 5 \times 10^5$ V/cm. The magnetoelectroreflectance was measured as described in Ref. 1, with the modification that the sample package was immersed in liquid helium and the experiments carried out at 1.5°K. PbS and cooled InAs and InSb detectors gave the required spectral sensitivity in the appropriate wavelength regions.

Figure 1 shows the magnetoelectroreflectance spectrum for direct valence to conduction band transitions in InAs at $\vec{k} = 0$. In order to emphasize the magnetic effects, we have subtracted off the electroreflectance background, $\Delta R/R$,

obtained in this case in the absence of a magnetic field. An oscillatory spectrum is seen to much higher energies than in conventional techniques, and in particular the spin splitting of the first main line is easily resolved. The upper insert shows the magnetoelectroreflectance spectrum associated with the onset of split-off valence to conduction band transitions for left and right circularly polarized incident radiation (σ_L and σ_R). In this case the background electroreflectance was smaller and was not subtracted off. Good agreement was obtained between the spectrum for the low energy valence to conduction band transitions and the corresponding magneto-absorption data of Pidgeon, et al.,[8] by associating the photon energies of the minima with the actual transition energies. This identification is maintained in higher energy regions where the spectra are not attainable by conventional magneto-absorption or reflection techniques.

In Fig. 2 are shown plots of the photon energy of the electroreflectance minima for the split-off valence to conduction band transitions as a function of magnetic field strength for the allowed transitions in the $\vec{E} \perp \vec{H}$ (σ_L and σ_R) spectrum. The solid lines give the transition energies calculated from effective mass theory[9,10] using energy band parameters which retain a good fit to the magneto-absorption data of Ref. 8. The spin splitting of these transitions is clearly resolved, and a reasonable overall fit obtained, except in the case of the first spin split line where the difficulty of assigning a resonance position to a dispersion shape on a sharply rising background electroreflectance curve may account for the error. From the intercept on the ordinate at $H = 0$, after subtracting off the energy gap $E_g = 0.41$ eV (Ref. 8), we obtain an experimental value for the spin-orbit splitting at 1.5°K of $\Delta = (0.38 \pm 0.01)$ eV. This should be compared to a value of 0.43 eV obtained by Matossi and Stern,[11] from a theoretical fit to absorption edge measurements on p-type InAs. From the computed levels obtained by an overall best fit to the magneto-absorption spectra of Ref. 8 and the magnetoelectroreflectance data of Fig. 2 we obtain the following values for the band edge effective mass and g-value of the split-off band; $m_{so} = (0.14 \pm 0.01)\, m_o$ and $g_{so} = (13.0 \pm 1.0)$.

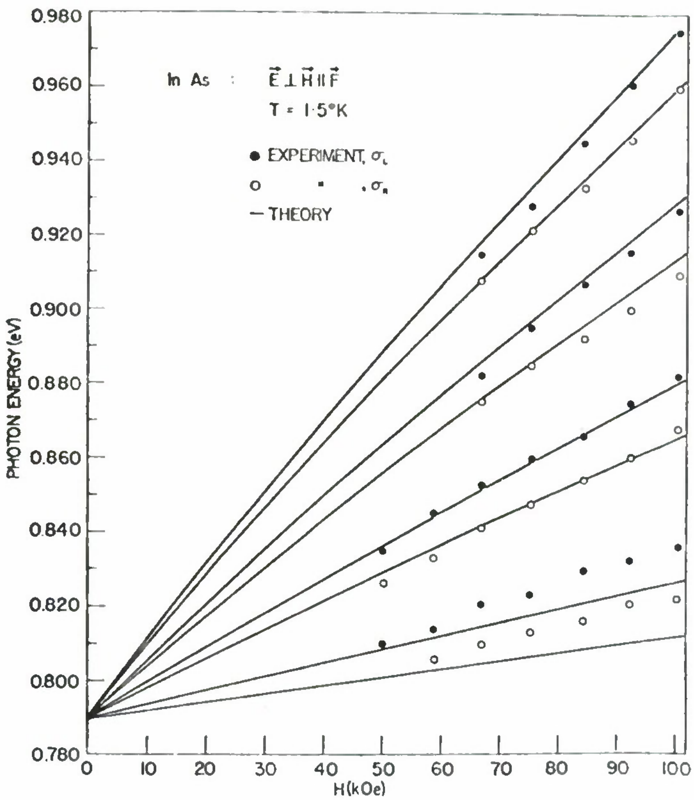

Fig. 2. Plot of the photon energy of magnetoelectro-reflectance minima for the split-off valence to conduction band transitions in InAs as a function of magnetic field strength. The circles show the experimental points. The solid lines give the theoretical energies for the allowed transitions, fitted to the experimental data as discussed in the text.

Further results for the magnetoelectroreflectance of the direct transition in InSb at 1.5°K and 84 kOe are shown in Fig. 3. In this case a great deal more spectral fine structure is observed in the low energy region than in the case of InAs and, further, very little background electroreflectance is obtained in the absence of a magnetic field. It appears that both these results may be associated with the much greater purity of the InSb ($N \sim 1.0 \times 10^{14}\,cm^{-3}$) than the InAs ($N \sim 2.0 \times 10^{16}\,cm^{-3}$) samples used. The oscillatory spectrum again extends from the energy gap to very high energies, merging into the onset of split-off valence to conduction band transitions. The solid arrows show the

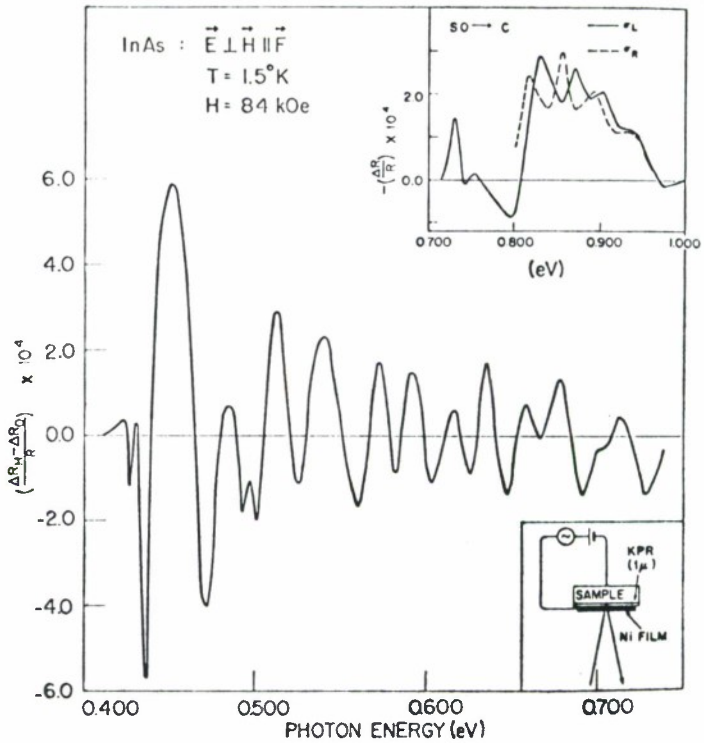

Fig. 3. Interband magnetoelectroreflectance in InSb for H = 84 kOe at T = 1.5°K. Inset shows the spectrum of the split-off valence to conduction band transitions, with the solid arrows showing the theoretical energies for these transitions.

positions of these latter transitions calculated from the effective mass theory for coupled bands of Ref. 10. Good agreement both as to position and spin splitting of these lines is obtained which is consistent with the upper limit of the spin-orbit splitting obtained previously by Aggarwal[5] using the piezo-reflectance technique (Δ = 0.81 ± 0.01 eV).

It is expected from the theory of Elliott and Loudon[12] that the transitions observed in magneto-optical spectra should be excitonic. Experimental evidence for this in InSb has been given by Johnson[13] from magneto-absorption studies. In fact, we observe very sharp symmetric lines both in the low energy magnetoelectroreflectance spectra of Fig. 3, and in the corresponding magneto-reflectance spectra. These line shapes seem characteristic of transitions to discrete exciton states, rather than the broader asymmetric lines one expects from transitions between Landau sub-bands where an integration over k_z is involved. There are two principal allowed (Δn = 0, -2) transitions in the first

set of lines between 0.250 and 0.260 eV. It appears that the first and third main lines are the exciton ground states associated with these, and that (in analogy with the work of Ref. 13) the higher energy shoulders may be associated with the first excited states. A further experimental and theoretical investigation of the detailed nature of the low energy spectral structure, and in particular of the additional unexplained strong lines near 0.256 eV and 0.275 eV will be the subject of another publication.

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13. ABSTRACT

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